IMPACT DAMAGE TOLERANCE OF THIN WALL COMPOSITE STRUTS

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Abstract

An experimental investigation was made to study the impact damage tolerance of thin wall composite struts made of both brittle epoxy and toughened epoxy based composite materials. Damage parameters such as barely visible surface damage and internal damage represented by the ultrasonic C-scan, and residual compressive strengths were evaluated against impact energy for two impactor sizes. From both a damage resistance (internal damage vs. impact energy) and a damage tolerance (residual compressive strength vs. internal damage) point of view, the toughened IM7/977-2 struts exhibited better performance than the brittle epoxy based T50/934 struts. This is attributed to the toughening mechanism in 977-2 which impedes delamination initiation from impact, and delamination growth and subsequent buckling under a compression loading. At barely visible damage thresholds, regardless of the impactor sizes, a maximum strength reduction of 45-55% was observed for the T50/934 struts, and approximately 10% for IM7/977-2 struts. This is of great interest for developing a damage tolerance design approach and risk assessment methodology in which the design allowable would bc defined by the residual strength at the threshold of barely visible damage.

Introduction

Impact damage in structural composites has received much attention during the last decade. Past experience has shown that strength reduction to both *tension* and *compression* loaded laminates can be caused by impact damage'. With increasing use of composite materials in spacecraft and flight instrument designs, this investigation was motivated by the concerns in flight hardware safety and reliability from the threat of unintentional impact due to extensive ground handling during flight hardware integration and testing. In literature, most researchers have focused on impact damage in coupons or simple plate configurations for the purposes of developing a building block design approach. Results from a limited number of studies showed that curvature effect can result in more severe damage in cylindrical shell structures than in simple plates[2-4]. Because of the geometrical differences and their influence on the effective boundary conditions during impact, the correlation between a simple plate and a small diameter cylindrical strut may be impractical.

In an exploratory study[5], the impact damage in thin wall composite struts made of high modulus fibers and a highly crosslinked brittle epoxy was found to be extremely harmful to its compression performance. A recent effort was also conducted to investigate the effects of impact damage on compression fatigue behavior of thin wall composite struts[6]. The present study extends the investigation of Ref. 5 to address the effects of other brittle epoxy and toughened epoxy based composites on impact damage tolerance, and the relevance of impactor size to the barely visible damage threshold. The goal of this study is to develop a damage tolerance design approach and risk assessment methodology for flight hardware using thin wall composite struts. The experimental procedure involves damaging struts at selected energies with two irnpactor sizes, estimating the size of the internal damage via ultrasonic C-scan, and measuring the residual compression strength. Details of the testing apparatus (Figs. 1-3) and procedures can be found in Ref. 5.

Material Systems and Strut Configurations

Two types of material systems were studied in this investigation; T50/934 and IM7/977-2. The T50/934, a composite with a highly crosslinked brittle epoxy, was used as the baseline material in this study since brittle epoxy based composites have been commonly used in previous flight hardware designs, The HMS/CE9015 used in Ref. 5 is also a brittle epoxy based composite material. As brittle epoxy based composites are found to be extremely susceptible to impact damage, new damage tolerant and. damage

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resistant resins have been formulated and proposed for structural composite applications. Toughened epoxy resins comprised of epoxy /thermoplastic blends (hat undergo a phase separation upon cure, such as 977-2, represent one of the approaches in introducing extrinsic toughening mechanisms into structural composites[7].

All struts were fabricated from unidirectional prepregs and cured in an external mold with an expandable mandrel. The unidirectional mechanical properties of the aforementioned structural composites are listed in Table 1. Similar to the HMS/CE9015 struts of Ref. 5, the T50/934 struts were 1.0 inch in diameter and had a $[5\ 15/0]_s$ layup, with zero degrees defined in the longitudinal direction of the strut. The IM7/977-2 struts were 2.5 inches in diameter and had a $[-1\ 28/0_3/-28/0_2]_s$ layup. The nominal wall thickness of the 1'50/934 struts is 0.03 inch, and 0.07 inch for the IM7/977-2 struts. Because of the differences in diameter and wall thickness, the resulting diameter-to-thickness ratio remains comparable between the two groups of struts, The corresponding predicted laminate properties are presented in Table 2 using the unidirectional properties of Table 1.

Impact Damage

Surface Damage. Among all the impact parameters (such as impact energy, contact force, delamination size, and fiber damage zone), *surface damage* is a parameter which is readily available immediately after the impact event, Because of the uncertainty in defining the impact parameters such as impact energy or force in the early design phase as well as in a post-impact assessment stage, and due to the complexity in using these parameters for predicting internal damage and residual mechanical performance[8-11], it is desirable to use surface darnage as a parameter for establishing a damage tolerance design approach and risk assessment methodology. In this investigation, one of the objectives was to explore the feasibility of using the barely visible damage (BVD) threshold as a damage tolerant design parameter. A BVD threshold is generically defined as the surface damage that is likely to be overlooked in a visual inspection process. Because of the variation in surface damage formation in different composite materials, the BVD threshold in laminates having different material systems or configurations (thickness, layup, or stacking sequence) should be defined on the merit of its own visibility metric. It is impractical to define a single visibility metric such as residual indentation for" all materials in all configurations.

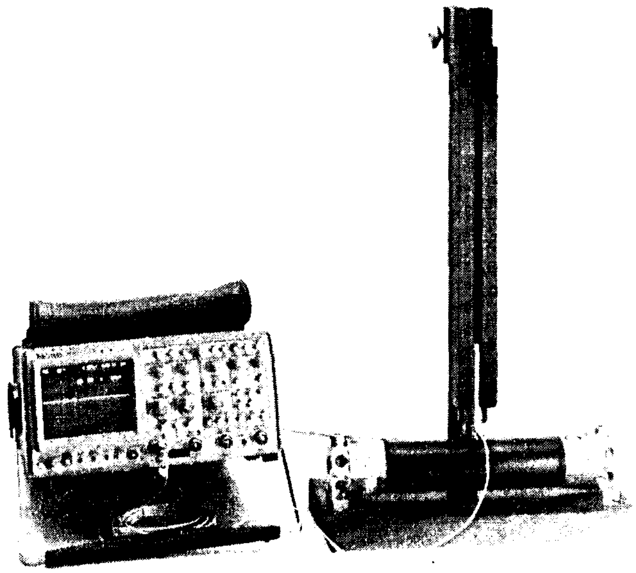

Fig. 1 Impact Fixture

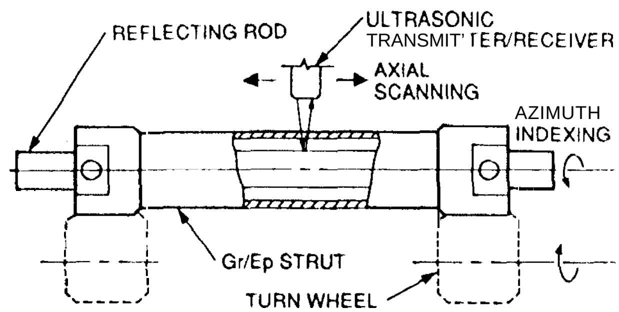

Fig. 2 Schematic of Ultrasonic Inspection

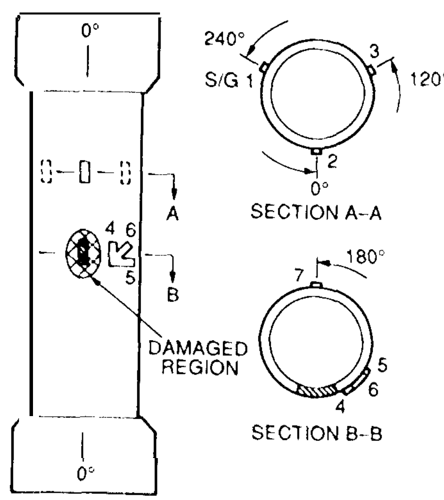

Fig. 3 Strut Instrumentation for compression Test

As shown in Fig, 4, the surface damage of the T50/934 struts featured matrix splitting (cracks between fibers) on both sides of the impact spot, which is similar to the surface damage of the HMS/CE9015 struts. When the impact energy was high enough, fiber breakage would occur in the same area of severe matrix splitting (Fig. 4). However, when the impact energy was low, a small number of minute matrix cracks with a length of less than 0.1 inch resulted from impact. There was no visible residual indentation or cracking directly under the impact spot. For practical purposes, the state of minute matrix splitting without fiber breakage was defined as the BVD threshold for the T50/934 struts. It was found that impact energy for the BVD threshold varied for different sizes of impactors. For the 0.5 inch and 2.0 inch diameter impactors, the BVD threshold of the T50/934 struts occurred when the impact energy was in the vicinity of 2 in-lb and 3-5 in-lb, respectively. The impact energy that produced the BVD in the T50/934 struts was found to be slightly less than the impact energy that produced BVD in the HMS/CE9015 struts. Nevertheless, the difference was small and might have be within the uncertainty range of the experimental procedure.

Because of the difference in the material systems and wall thicknesses, surface damage of the IM7/977-2 struts was completely different from that of the T50/934 struts. There was typically no discontinuity feature such as cracks imparted by the low energy impact for the IM7/977-2 struts. Instead, a small residual indentation (approximately less than 0.1 inch diameter) appeared under the impact spot. As the impact energy increased, surface cuts (cracks through fibers) as shown in Fig. 5 became visible. Typically, such surface cuts run in the direction normal to the fiber orientation with the number of the surface cuts increasing as the impact energy increased. In this study, a surface cut with a length of less than 0.1 inch was defined as the BVD threshold. Impact energies at the BVD threshold were found in the vicinity of 15 and 25 in-lb for the 0.5 and 2.0 inches impactors, respectively, It is worth mentioning that, even with the BVD on the outside surface of the struts, damage was always evident on the inside surface of all the T50/934 and IM7/977-2 struts, Access limitation for inside inspections in integrated flight hardware makes the. inside surface damage information useless for most applications. Therefore, inside surface damage information was not considered in this investigation.

Internal Damage. For a thin wall composite strut, a low velocity impact can introduce a wide variety of three dimensional damage including multiple delamination, fiber damage, and transverse matrix cracking. When assessing impact damage in integrated flight hardware, it will be difficult, if not impossible, for an in-situ non-destructive evaluation technique to attain a comprehensive assessment of damage in a cost effective manner. One of the objectives in this investigation was to establish a *through-the-thickness damage projection* via ultrasonic C-scan as a damage parameter for use in damage tolerance prediction and risk assessment criteria. To this end, an ultrasonic inspection scheme developed in a previous study[5] was used. While this scheme provided a controlled and expeditious laboratory procedure for acquiring the ultrasonic C-scan data base, the scheme may be of limited or no use for in-situ flight hardware evaluation because of the need of a reflecting rod inside the strut for the pulse echo ultrasonic technique.

Through-the-thickness C-scan images of the T50/934 and IM7/977-2 struts are shown in Figs. 6 through 9. All the struts exhibited ellipse-like damage which has been correlated to delamination formation in previous studies via microscopic examination of dissected strut specimens[5,12]. For the T50/934 struts, at low impact energy, the 0.5 inch impactor produced a wider damage in the circumferential direction than the 2.0 inch impactor did. Whereas, at high impact energy, the converse was true.

From the pre-impact C-scan images, the lM7/977-2 struts were found to have a very irregular material quality as evidenced by the inhomogeneity in ultrasonic attenuation of Figs. 8 and 9. The material inhomogeneity may be caused by resin porosity or fiber waviness as a result of the fabrication process. Since both the impact damage (such as delamination) and material inhomogeneity (such as porosity) registered similar ultrasonic attenuation in the C-scan image, verification of impact damage in Figs. 8 and 9 required careful comparisons between the pre-impact and post-impact C-scan images.

To quantify the damage, an approach of postulating the. best fit ellipse(s) to the C-scan image. was proposed[5]. Damage dimensions were defined by the major axis of the postulated ellipse.(s). For the T50/934 struts, at high impact energy, multiple delaminations damage was evident. Whereas all the IM7/977-2 struts appeared to have single delamination damage. only. Strut S/N 26 which has been double impacted accidentally has a two ellipse-like damage image in Fig. 8.

Impact Damage Tolerance

impact damage in a composite strut entails two separate issues; *damage resistance* and *damage tolerance*. Both damage resistance and damage tolerance are important to the design consideration, although damage tolerance is solely a concern of risk assessment, In order to gain insight into the two physically different issues, test results were evaluated accordingly.

Damage Resistance. Damage resistance is a measure of the ability of a material or structure to limit the degree of damage resulting from an impact, In other words, the impact parameter (energy, etc..) is an independent variable, and the degree of damage is a dependent variable. In this investigation, the degree of damage was measured in terms of the through-the-thickness C-scan image of the internal damage. Comparisons of damage resistance characteristics among all struts are shown in Fig. 10 in which individual sizes of the postulated delamination(s) are included. Because of the difference in wall thickness between the two groups of struts, the impact energies in Fig. 10 are normalized by their respective wall thickness. For each group of struts and test configurations, boundaries enveloping the maximum damage dimensions are shown in Pig. 10. Within each group of materials, a 2.0 inch diameter impactor was found to impart less damage than a 0.5 inch impactor would, which is consistent with engineering intuition.

Among all the strut specimens, the IM7/977-2 struts exhibited the highest degree of damage resistance, This is attributed to the toughened epoxy resin, 977-2, in the composite, Between the two brittle epoxy based composite struts, the 1'50/934 struts were found to have a greater resistance to impact damage. It is interesting to note that internal damage dimensions of both the T50/934 and IM7/977-2 struts are about the same at their respective BVD thresholds. This means that for these two groups of struts, the damage resistance characteristics were comparable when the BVD threshold was used as the impact parameter.

Damage tolerance. Damage tolerance is a measure of residual mechanical capabilities of a material or structure having a specific amount of damage, regardless of the mechanism in which the damage was introduced. Hence, in this investigation, the independent variable is the degree of internal damage, and the residual compressive strength is the dependent variable. All struts were tested to failure under compression loading. Similar to the HMS/CE9015 struts of Ref. 5, delamination buckling always preceded the ultimate failure of the T50/934 struts, In contrast, the IM7/977-2 struts all resulted in compressive fracture failure. The difference in failure modes between the two groups of struts was believed to be largely attributed to the improved damage tolerance characteristics (i.e., impeded delamination growth) of the toughened 977-2 epoxy resin. The ultimate compressive strengths of all the struts are summarized in Fig. 11 against the internal damage dimensions, Boundaries enveloping the maximum strength reductions for each group of struts arc also shown in Fig. 11. A comparison of these enveloping boundaries indicates that the IM7/977-2 struts were more damage tolerant under compression than were the T50/934 struts. The relative high compressive strength reduction of the T50/934 struts is believed to be largely attributed to delamination buckling preceding ultimate failure, which may be impeded by the toughened epoxy in the IM7/977-2 struts.

However, from an open-hole coupon compression test, it was learned that both the T50/934 and IM7/977-2 coupons exhibited a similar compressive fracture failure mode, and had approximately the same strength reduction with respect to the open-hole size (Fig, 11). Comparing the impact damage and open hole effects on the compressive strength reduction indicates that the extrinsic. toughening mechanism in a cured 977-2 epoxy was beneficial in impeding delamination growth, but not in impeding compressive fracture failure. Therefore, one may expect that a toughened epoxy, such as 977-2, can be beneficial in impact damage resistance and in damage tolerance for a compression loaded structure, but not in damage tolerance for a structure which will fail in tensile fracture such as a graphite/epoxy composite overwrapped pressure vessel. For the T50/934 struts with an open-hole, the strength reduction was found to be more severe than the coupon with an open-hole (Fig. 11). The additional strength reduction is believed to be caused by bending (toward the single open-hole) as observed during the compression test.

Design Approach/Risk Assessment Methodology. Customarily, damage resistance and damage tolerance arc combined in design considerations, Strength reductions are therefore expressed in terms of impact energy directly (Fig. 12). As expected, given the same impact energy, the 2,0 inch diameter impactor yielded a less severe strength reduction than the 0,5 inch impactor did, However, within the same material group, the maximum strength reductions at the BVD thresholds were approximately in the same range for both sizes of impactors, i.e., a 45-55 % reduction for T50/934 struts and approximately 10% for IM7/977-2 struts. From this observation, one may suggest that regardless of the impactor size, composite struts of the same material and configuration may have similar strength reductions at BVD thresholds. This is of great interest for developing a damage tolerance design methodology in which the design allowable will be defined by the residual strength at the BVD threshold, and a risk assessment methodology in which accept/reject criterion will be established by the BVD. The use of BVD threshold as an impact parameter in thin wall composite strut design has advantages over other parameters such as energy, force, and velocity. First, as mentioned above, strength reductions in thin wall composite struts having the BVD were found to be approximately the same regardless of the impactor size. Second, the use of BVD threshold does not require a quantitative definition of the impact event in the early design phase, nor in the post-impact risk assessment activities.

Conclusion

An experimental investigation was made to study the impact damage tolerance in thin wall composite struts. impact damage entails two separate issues; damage resistance and damage tolerance. From the view point of damage resistance, the IM7/977-2 struts exhibited better performance than the T50/934 and llMS/CE9015 struts did. That is, given the same amount of impact damage, smaller internal damage was accrued in the IM7/977-2 struts. This is attributed to the use of toughened epoxy resin, 977-2, in the composite. From the damage tolerance point of view, the IM7/977-2 struts were shown to have less compressive strength reduction for the same degree of internal damage, Under compression loading, delamination buckling always preceded the ultimate failure of the T50/934 struts. Whereas the IM7/977-2 struts consistent y failed through compressive fracture. The difference in failure modes between the two groups of struts was attributed to the improved damage tolerance characteristics that impeded delamination growth and subsequent buckling in the 977-2 resin.

For design considerations, it is customary to combine damage resistance and damage tolerance characteristics by relating residual compressive strength to a given impact energy. Within the same material group, strength reductions at the BVD thresholds were found to be independent of the impactor sizes, i.e., 45-55% reduction for T50/934 struts and approximately 10% for IM7/977-2 struts. Based on this finding, a damage tolerance design and risk assessment methodology in which the design allowable would be defined from the residual strength at the BVD threshold is proposed for the thin wall composite struts. In this investigation, matrix splitting on both sides of the impact spot was the surface damage feature of the brittle epoxy based T50/934 and HMS/CE9015 struts, and surface cut(s) for the toughened IM7/977-2 struts. Because of the variation in surface damage formation under impact, the BVD threshold in thin wall composite struts of different materials and configurations should be defined on the merit of its own visibility metric. It is impractical to define a single visibility metric such as residual indentation for all materials and structural configurations.

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Table 1 Properties of Graphite/Epoxy Composites

1'	IM7/977-2	T50/934~~/CE9015	
E_L^t	**26.0 Msi**	31,3 Msi	**32.3 Msi**
E_L^c	**21.4 Msi**	29.2 Msi	**27.7 Msi**
E_T^t	**1.51 Msi**	1,05 Msi	**1.17 Msi**
E_T^c	**1.45 Msi**	1.04 Msi	-----
G_{LT}	**0,88 Msi**	0.67 Msi	**0,85 Msi**
ν_{LT}	0.30	0.28	**0.24**
x'	343.2 Ksi	**161,9 Ksi**	**230.4 Ksi**
X^c	165.3 Ksi	**82.9 Ksi**	106.8 Ksi
Y^t	9.8 Ksi	**4,4 Ksi**	4,6 Ksi
Y'	25.4 Ksi	**23.3 Ksi**	-----
s	15.8 Ksi	**8.4 Ksi**	6.6 Ksi
' tension, L longitudinal	c compression, T transverse		

Table 2 Predicted and Measured Strut Material Properties

Material Layup Thickness	IM7/977-2 $[\pm 28/0_3/-28/0_2]_s$ 0.070 inch	T50/934 $[\pm 15/0]_s$ 0.030 inch	HMS/CE9015 $[\pm 15/0]_s$ 0.025 inch
E_{xx}^t	22.1 Msi	26.9 Msi	28.0 Msi
E_{xx}^c (Measured)	18.3 Msi (16,7 Msi)	25.2 Msi (27.8 Msi)	24.2 Msi (28.4 Msi)
E_{yy}^t	1,82 Msi	1.11 Msi	1.26 Msi
E_{yy}^c	1.72 Msi	1.10 Msi	1.25 Msi
G_{xy}	2.02 Msi	1.89 Msi	2.08 Msi
ν_x	0.83	1,27	1.14
Ultimate Compression Failure Load			
Max. Strain Tsai-Wu (Measured)	80,967 lb 57,940 lb (58,457 lb)	6,537 lb 4,361 lb (7,670 lb)	7,147 lb 4,420 lb (5,118 lb)
x, y properties referenced to strut longitudinal and circumferential directions.			

1.0" **DIAMETER T50/934 STRUTS**

(0.5" **DIAMETER IMPACTOR; 7.0 in-lb IMPACT ENERGY)**

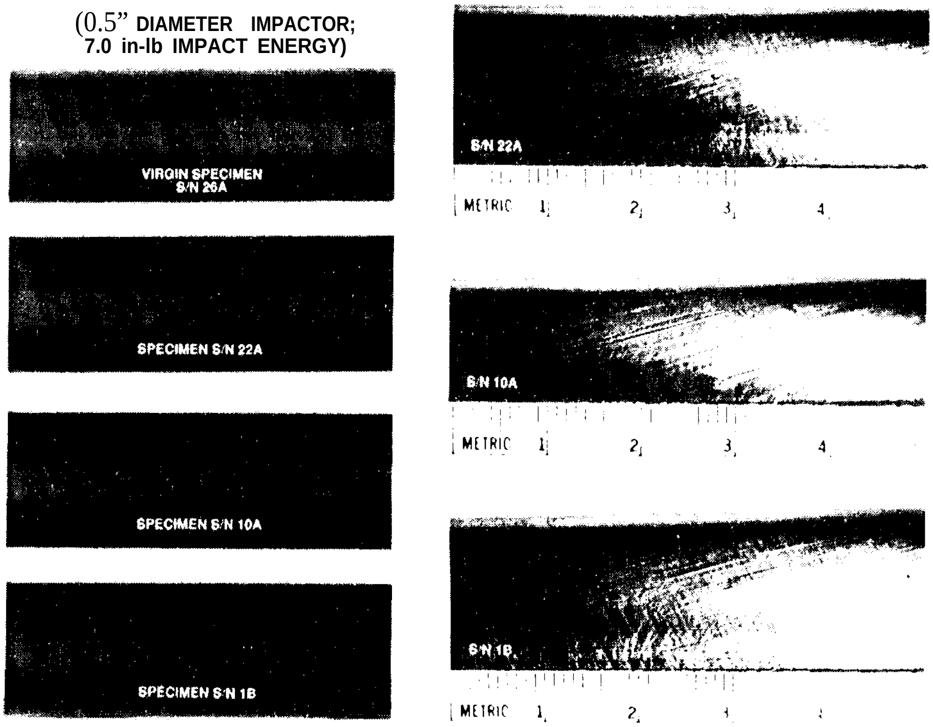


Fig. 4 Typical Surface Damage of T50/934 Struts

2.5" **DIAMETER IM7/977-2 STRUTS**

(0.5" DIAMETER IMPACTOR; 35.0 in-lb IMPACT ENERGY)

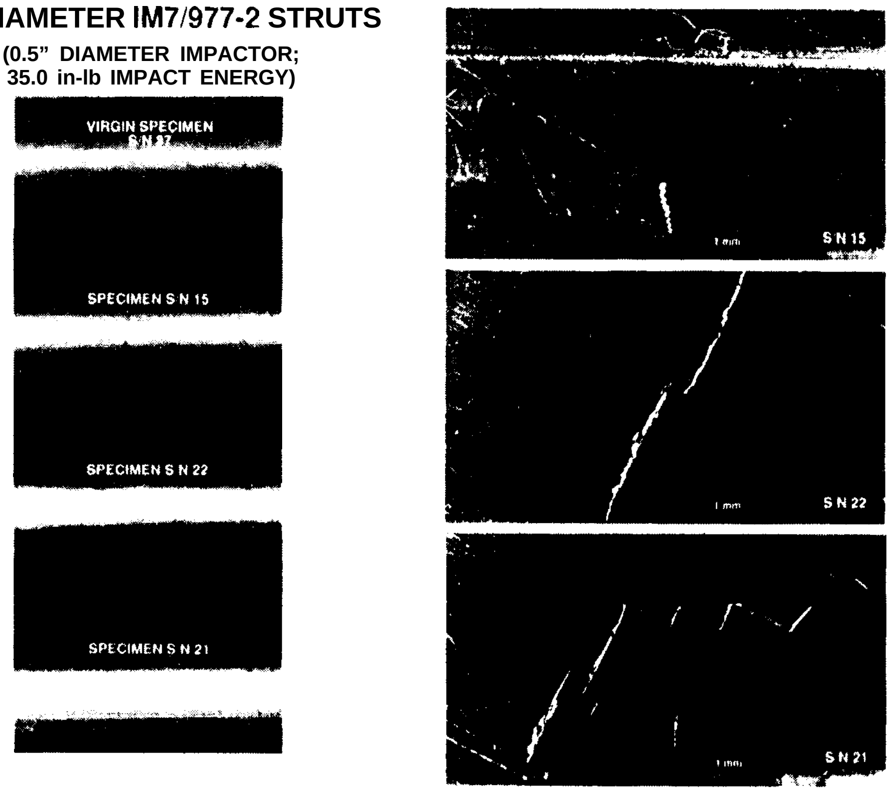


Fig. 5 Typical Surface Damage of IM7/977-2 Struts

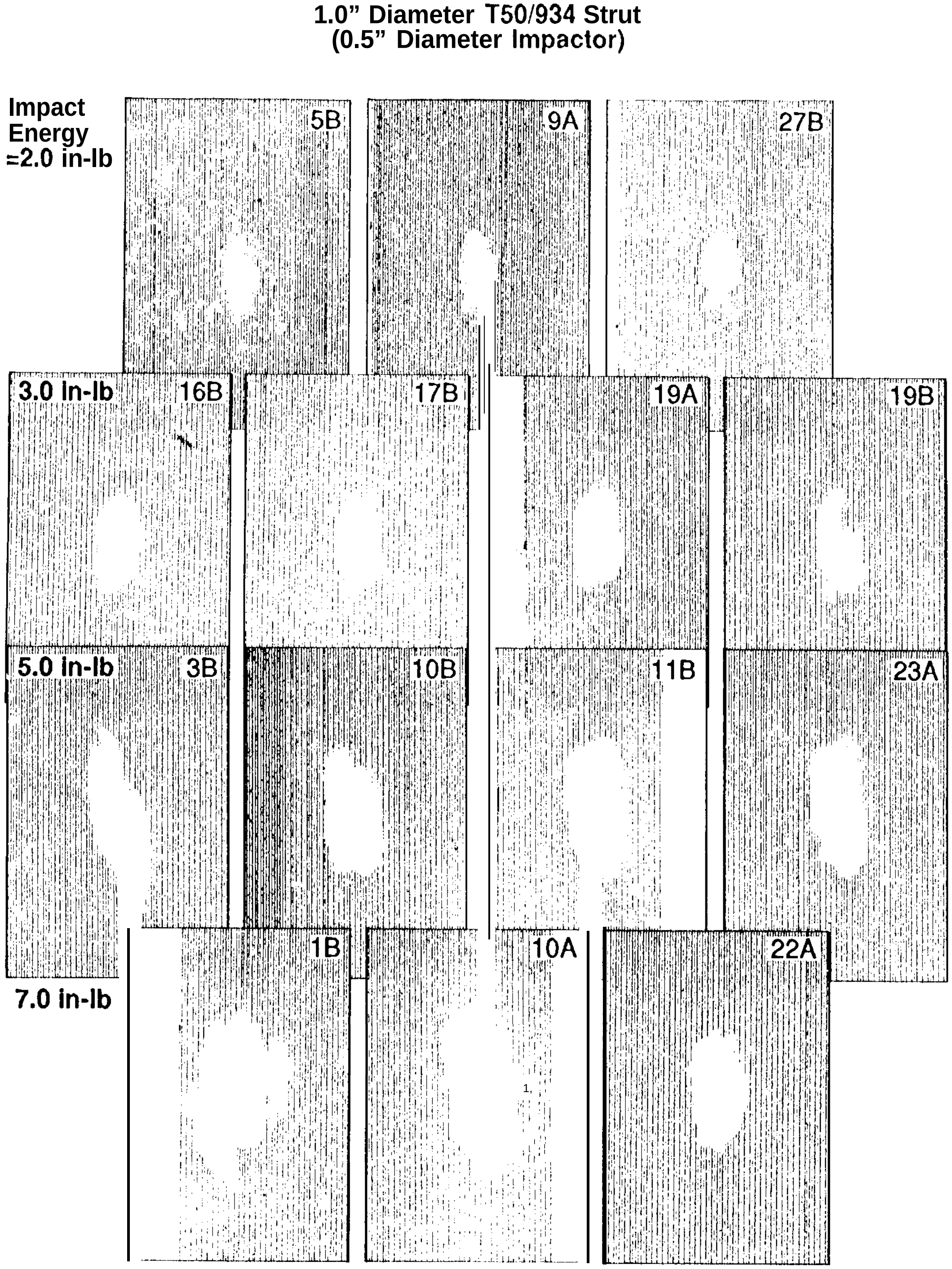


Fig. 6 C-Scan Image of T50/934 Struts (0.5 inch impactor)

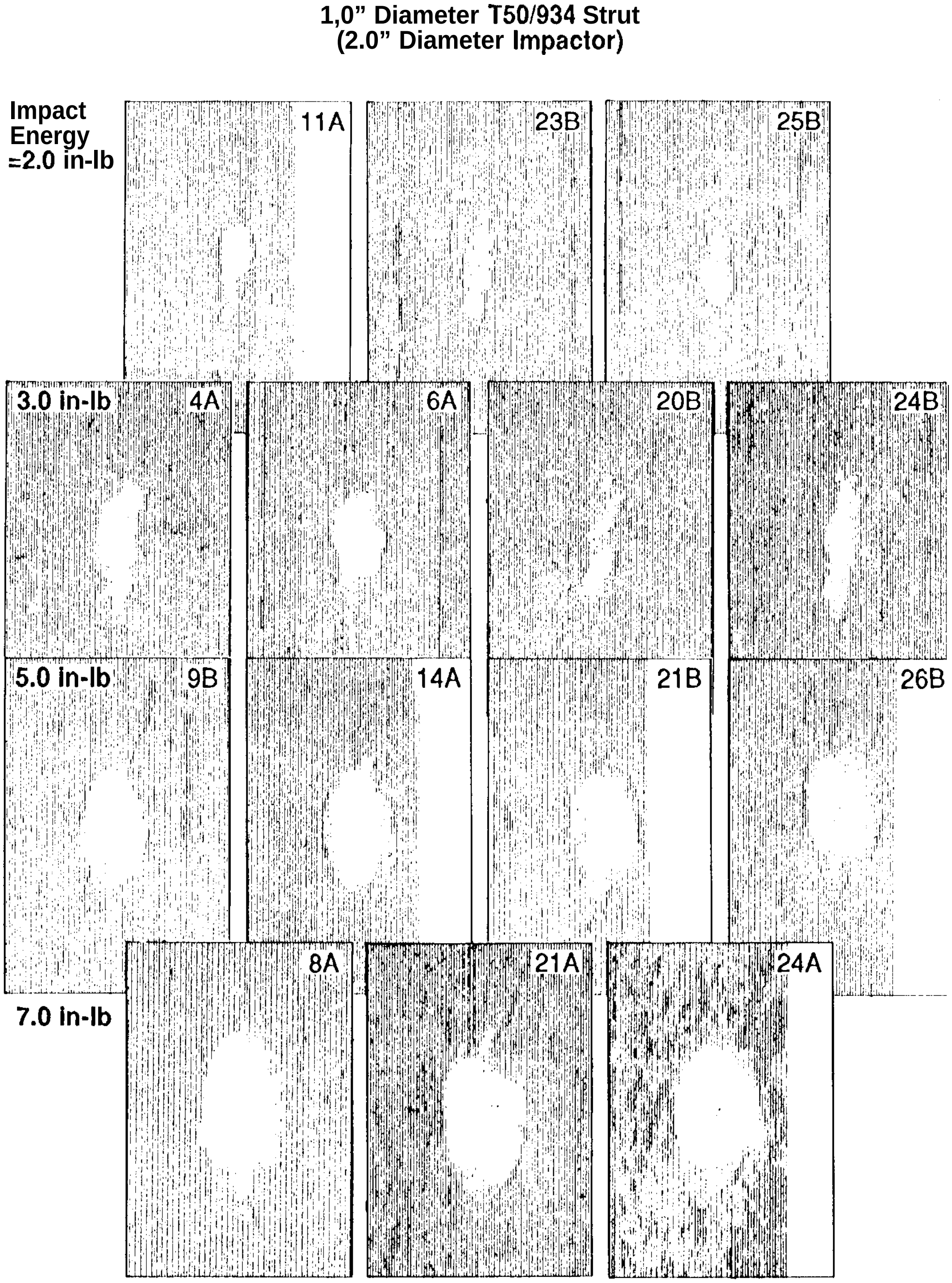


Fig. 7 *C-Scan* Image of T50/934 Struts (2.0 inch impactor)

2.5" Diameter Struts
(0.5" Diameter Impactor)

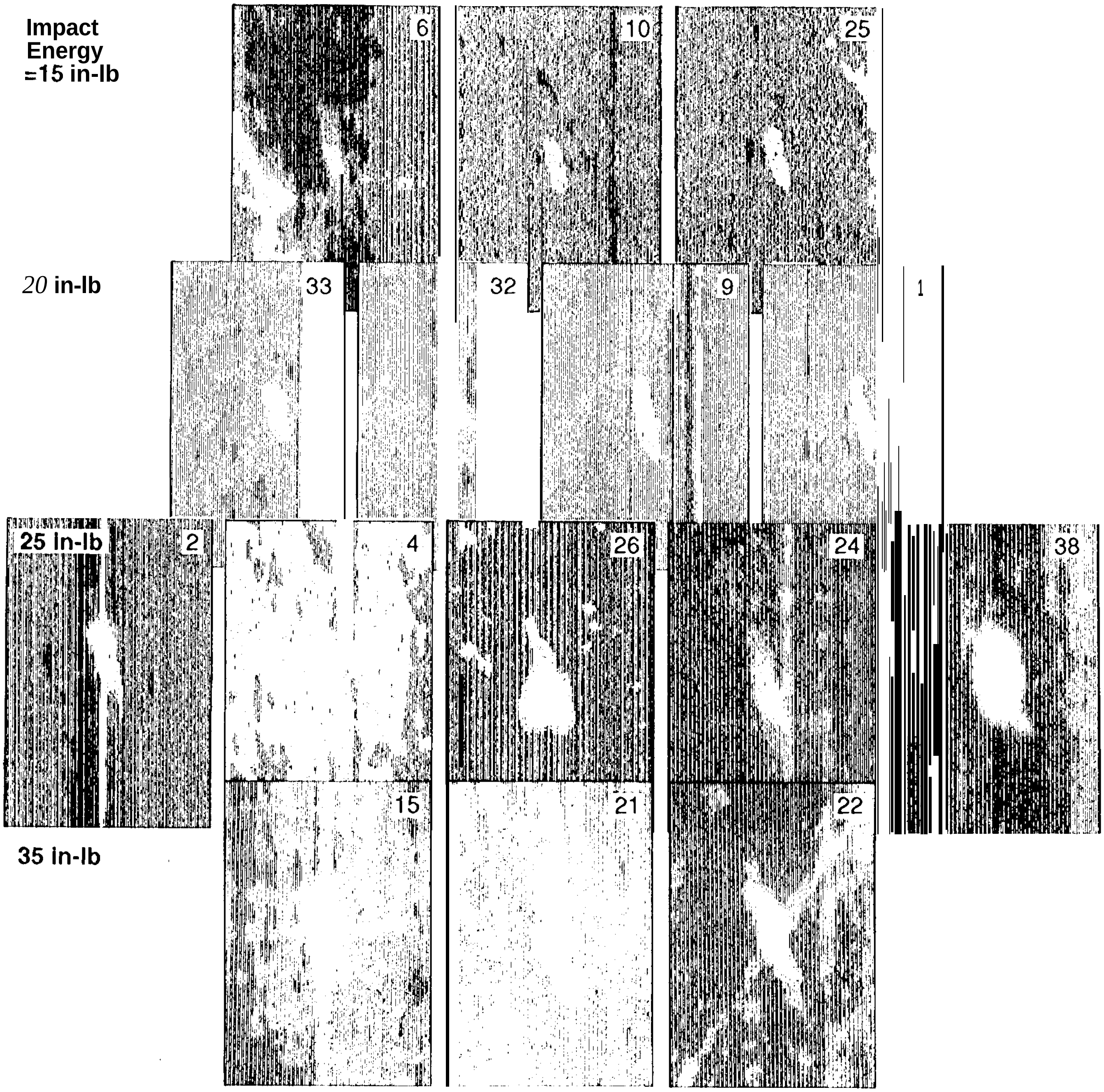


Fig. 8 C-Scan Image of IM7/977-2 Struts (0.5 inch impactor)

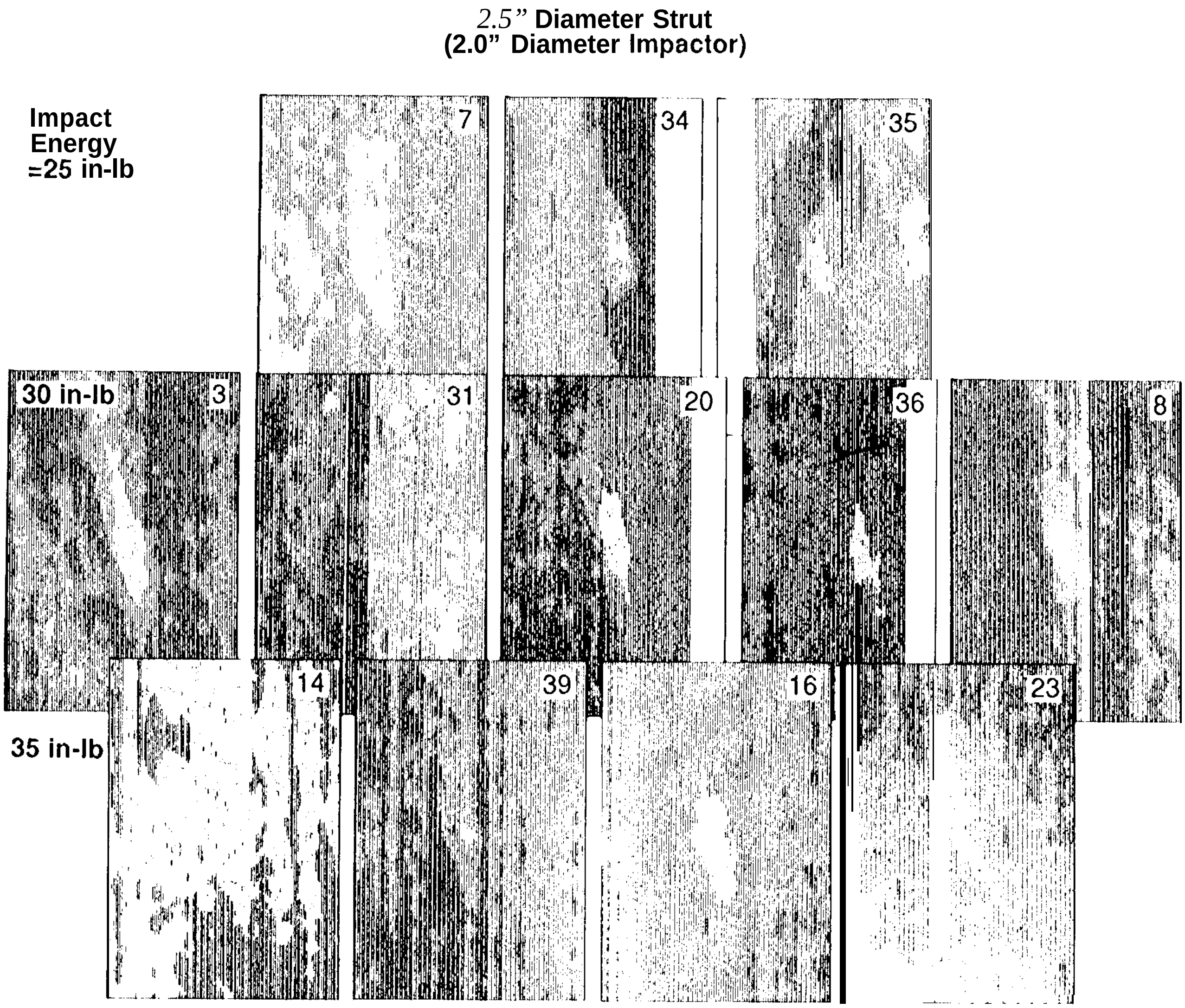


Fig. 9 **C-Scan** Image of IM7/977-2 Struts (2,0 inch impactor)

0 }]M5/(J9015 (().5" Impactor)

A T50/934 (0.5" Impactor)

▲ T50/934 (2.0" Impactor)

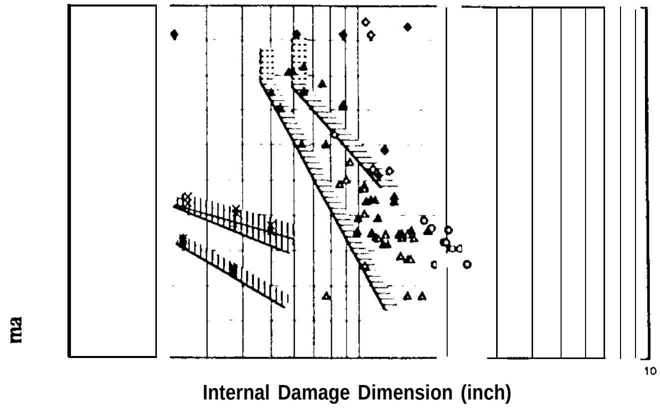
o IM7/977-2 (0.5" Impactor)

◆ IM7/977-2 (2.0" Impactor)

+ T50/934 (coupon w/hole)

X IM7/977-2 (coupon w/hole)

⋊ T50/934 (strut w/hole)



Fig, 11 Residual Compressive Strength vs. Internal Damage

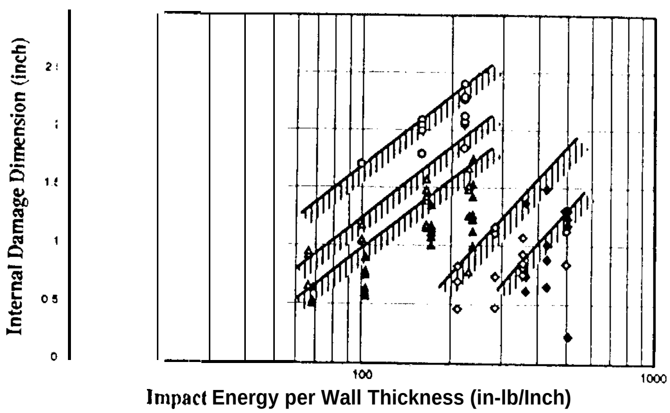
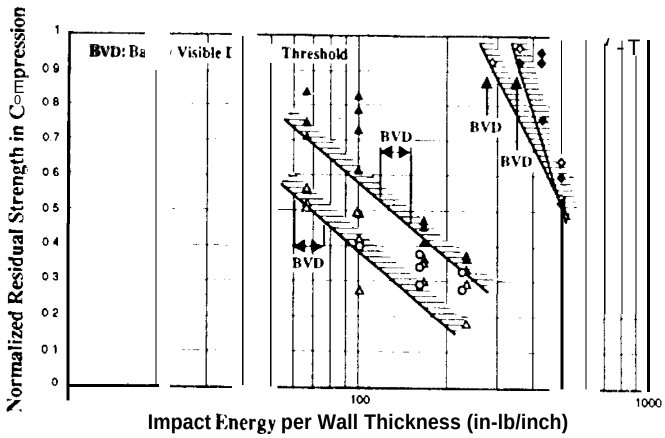


Fig. 10 Internal Damage vs. impact Energy



Fig, 12 Residual Compressive Strength vs. Impact Energy